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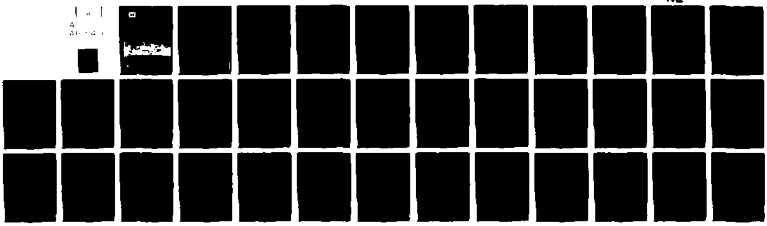

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ACOUSTIC EMISSION FROM CONCRETE SPECIMENS

by

P. F. Mlakar, R. E. Walker, B. R. Sullivan

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U. S. Army Engineer Waterways Experiment Station
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September 1981

Final Report

Prepared for Assistant Secretary of the Army (R&D)
Department of the Army
Washington, D. C. 20310

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Six monotonic and six cyclic load compression tests on 6- by 12-in. cylindrical concrete specimens were monitored for acoustic emission. Fundamental data were collected and analyzed and the Kaiser effect was observed. The data are presented as counts versus events to aid in the identification of source characteristics. One multiaxial load (compression and tension) test was also monitored. The slope of counts versus event curve for this primarily tension

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20. ABSTRACT (Continued).

test differed from those of the curves for the primarily compression test. This difference suggests that the source characteristics of concrete acoustic emissions can be empirically separated and identified.

Preface

This investigation was performed by the U. S. Army Engineer Waterways Experiment Station (WES) under Department of the Army Project No. 4A161101A91D, In-House Laboratory Independent Research (ILIR) Program, sponsored by the Assistant Secretary of the Army (R&D).

The study was conducted during the period April 1979-September 1980 by Dr. P. F. Mlakar and Messrs. R. E. Walker and B. R. Sullivan of the Structures Laboratory (SL), WES, and Mr. J. L. Pickens of the Instrumentation Services Division, WES. This report was written by Dr. Mlakar, Mr. Walker, and Mr. Sullivan.

The work was conducted under the supervision of Messrs. B. Mather, Chief, SL, W. J. Flathau, Assistant Chief, SL, J. T. Ballard, Chief, Structural Mechanics Division, SL, and Mr. J. M. Scanlon, Jr., Chief, Concrete Technology Division, SL.

Commanders and Directors of WES during this study and preparation and publication of this report were COL J. L. Cannon, CE, COL N. P. Conover, CE, and COL T. C. Creel, CE. Mr. F. R. Brown was Technical Director.

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Conversion Factors, U. S. Customary to Metric (SI) Units of Measurement

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
gravity	9.806650	metres per second squared
inches	0.0254	metres
inches per second	0.0254	metres per second
kips (force)	4.448222	kilonewtons
microinches	0.0254	micrometres
pounds (mass)	0.4535924	kilograms

ACOUSTIC EMISSION FROM CONCRETE SPECIMENS

Introduction

Background

1. Acoustic emission is the term generally applied to the phenomenon in which a material or structure gives off transient vibrations when stressed. These acoustic emissions have been studied in connection with the deformation, fracture, and fatigue of metals and composite materials such as concrete, rock, and soil. They have been usefully employed in the proof testing of machined parts and in the detection of flaws in welding processes.

2. As these acoustic emissions are indicators of increasing stress levels in and potential subsequent deformation of a structure, they could also possibly be used to determine nondestructively the degree of damage which a structure has suffered. Such a technique would have many applications to various concrete structures of interest to the U. S. Army Corps of Engineers. The technique could be useful in assessing the residual protection offered by a structure that has been severely stressed by a previous weapon loading. The method might also be used in evaluating the remaining integrity of a structure that has been subjected to a strong-motion earthquake. Such a procedure could generally be employed in estimating the in-service ability of a structure to carry loads in excess of those anticipated during its original design.

Purpose and scope

3. Accordingly, the investigation reported herein was undertaken to judge the feasibility of in-service assessment of structural damage by acoustic emissions. This study began with a critical review of previous acoustic emission research related to concrete structures. Then, appropriate hardware to monitor the acoustic emissions from such structures was acquired and used during the compression testing of standard concrete cylinders and biaxially stressed hollow cylinders. Finally, the data from these experiments were reduced to characterize

the acoustic emissions from concrete.

Review of Related Acoustic Emission Research

4. The confident application of acoustic emission phenomena to the nondestructive evaluation of structural safety requires (a) an understanding of the basic mechanisms within structures and materials that generate microseismic stress waves; (b) a knowledge of the process by which these disturbances are propagated through the structure; and (c) the development of instrumentation to identify accurately the nature, severity, and location of the source of the emission. The considerable research devoted to these general requirements was summarized in Liptai, Harris, and Tatro (1972); Spanner (1974); and Spanner and McElroy (1975). Judging from the presentations during the International Conference on Acoustic Emission at Anaheim, California, in September 1979, further study is still under way in all these areas. Nonetheless, both today's open literature and reports published by acoustic emission hardware vendors abound with useful applications of acoustic emission technology to various but specific structural problems. These problems include the in-flight detection of aircraft cracks (Bailey and Pless 1976), weld quality monitoring (Kumar 1974), field testing of fiber-reinforced plastic structures (Fowler 1977), and the prediction of incipient embankment instability (Koerner, Lord, and McCabe 1978).

5. However, the specific application of this technology to the types of concrete structures of interest to the Corps has not yet been the subject of extensive research. Some investigators have begun to catalog the acoustic emissions of concrete material specimens or simple structural elements during laboratory experiments (Bickle and Smiel 1975; Fertis 1976; McCabe, Koerner, and Lord 1976; Nielsen and Griffin 1977; Ingersoll and Popovics 1979; Naus 1979; and Kobayoshi et al. 1980). Before this technique can be practically employed in the field evaluation of Corps structures, research must successfully relate these laboratory results to the generating mechanisms within the structure and resolve the as yet undefined instrumentation difficulties imposed by the unique environments of these structures.

Experimental Setup and Instrumentation

Test procedures

6. During the first series of tests, several concrete cylinders 6 in.* in diameter by 12 in. in length were tested at the U. S. Army Engineer Waterways Experiment Station (WES) for acoustic activity during loading. Data on the concrete are given in the following tabulation:

Cement:	ASTM: C 150, Type II (American Society for Testing and Materials 1981)
Aggregate:	Crushed limestone coarse, 3/4-in. nominal maximum size; natural sand fine
Air Content:	Approximately 5 percent
Water-Cement Ratio:	0.5 by mass

The specimens were moist-cured for 14 days, allowed to dry in laboratory air for 14 days,** and then treated to have their ends ground plane and parallel before testing. The cylinders were loaded in compression at a rate of 60 kips per minute until failure. A small preload of 0.1 percent of the ultimate load was used to seat the loading heads. Some of the cylinders were held at 60 kips for approximately 30 sec before the loading was resumed. Others were unloaded after reaching 60 kips and reloaded at the same rate to study the Kaiser effect. Failure occurred at loads between 100 and 150 kips on all cylinders. A second test was conducted on a hollow cylinder 13 in. in inside diameter, 15 in. in outside diameter, and 29 in. long. Loading was biaxial in longitudinal compression with hoop tension. The WES Structures Laboratory's hydraulic ram was used to load axially and at the same time pressurize a fluid within the cylinder. The major item of interest was the tensile acoustic emissions.

Instrumentation

7. All uniaxially loaded cylinders were strain gaged in a manner

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* A table of factors for converting U. S. customary units of measurement to metric (SI) units is found on page 3.

** The practice of allowing the specimen to dry prior to compression testing is in violation of standard requirements but was adopted for these tests since it was believed to produce a specimen in which acoustic emission would be maximized.

that cancelled tension strain readings and allowed only compressional strain to be recorded. The strain gages measured the average surface strain for a 6- by 1/4-in. area. Two acoustic sensors were attached with electrical tape directly to the concrete surface, 180 deg apart, 90 deg from each strain gage, at the center of the cylinder (Figure 1a). The biaxially loaded cylinder setup is shown in Figure 1b. These acoustic transducers were Dunegan/Endevco Model S140B/LD with a resonant frequency of 140 kHz, capable of resolving surface waves having accelerations of the order of 10^{-12} g's.

8. The following signal-conditioning and recording equipment was used:

a. Strain gage bridge balance amplifier system (WES #DAM 103).

b. Dunegan/Endevco Model 3000 series system.

(1) Acoustic Emission Preamplifier Model 1801P.

(2) Dual-Signal Conditioner Model 302A.

(3) Dual Counter Model 303.

(4) Distribution Analyzer Model 920A.

c. Magnetic tape recorder: Sangamo Sabre V with wide-band II frequency modulation (FM) configuration.

d. Hewlett-Packard Model 7046A X/Y/Y recorder.

Techniques and procedures used

9. Since the tests to be conducted were destructive, it was felt that some method of storing the data was necessary. The only method that would store the high-frequency bursts over a period of 2-3 min was a high-speed magnetic tape recorder with a frequency response of at least 500 kHz. Using a Sabre V with wide-band Group II FM allowed recording of an unlimited number of up to 10-v bursts at 120-in./sec tape speed for 15 min. The FM mode was also used for recording load and strain data.

10. The raw data were amplified by the 1801P preamplifier and the 302A signal conditioner at 80 db for recording. This level resulted in maximum acoustic bursts of 10-v amplitude. The tape recorder was adjusted to record at 10 v full scale. The block diagram in Figure 2 shows the connections for the tape recorder. The two acoustic transducers,

load cell, strain gage, and a timing signal were simultaneously recorded for future playback and analysis. Subsequent plots were made from the tape showing load versus strain, load versus counts, load versus events, and counts versus events.

11. When 1.0-v full-scale signals were played back into the 302A signal conditioner and the signal was amplified at 20 db, a 10-v signal was presented to the 303 counter, just as the on-line signal was. The "tape reproduce" signal bypassed the 1801P preamplifier and was connected directly to the 302A signal conditioner through a 0.01-μF capacitor (since the 302A input is biased at +28 v direct current).

12. The 920A distribution analyzer provides a direct current age proportional both to the number of counts and to the number of events. These 10-v maximum voltages are suitable for driving an X/Y plotter.

13. The following settings were determined to be the optimum for plotting the acoustic emission data for the concrete tests:

a. Gain: 80 db.

b. Multiplier: 1.

c. Event dead time: 100 μsec.

d. Auto reset, counts: 10 kHz.

e. Auto reset, events: 1 kHz.

14. Because the raw data were recorded on tape, it was possible to experiment with the settings on the 920A distribution analyzer to produce quality plots. Otherwise several tests would have been necessary to determine optimum gains and trigger levels, increasing costs.

Test Results and Analysis

15. Conventional load-strain and strength data are given in Figures 3-5. The corresponding acoustic emission event and count data measured as described previously are presented in Figures 3-11. The monotonic loading data are shown in Figures 6 and 7 for comparison with the cyclic load data as shown in Figures 8-11. The Kaiser effect was evident in all cyclic load tests, but it should be pointed out that these specimens did not have a rest period during load cycling.

16. Since the data were recorded on tape, graphs of cumulative counts versus cumulative events could be made. They are shown in Figures 12-17. Note the linear nature of the relationship.

17. In Dilipkumar, Gudimetla, and Wood (1979), an expression relating cumulative counts, events, threshold level, and an amplitude-distribution parameter has been given. It is of the following form:

$$N = \left(\frac{Pf\tau}{b}\right)\left(\frac{V_o}{V_t}\right)^b$$

where

N = cumulative counts

P = cumulative events

f = resonant frequency of the transducer

τ = decay time of the burst

b = amplitude-distribution parameter

V_o = a level below which no detection is possible

V_t = threshold level

Dilipkumar, Gudimetla, and Wood (1979) used this equation to develop a simplified method of amplitude-distribution analysis. Their results indicate that reasonable accuracy can be obtained by plotting N versus P in determining the parameter b. Therefore a plot of N versus P characterizes amplitude-distribution. The parameter b can be obtained without special equipment and can also be used to quantify the fracture mechanism. The linear nature of the data in Figures 12-17 was observed, the data were graphically fit to a straight line, and the slope was determined.

18. The events per thousand counts for each of the two transducers in the four monotonic and four cyclic tests are given in Table 1. These data were obtained by graphically estimating the slope of the cumulative events versus cumulative counts curve for each transducer in each test. A statistical analysis of the variance (Miller and Freund 1977) of this parameter is summarized in Table 2. According to this summary, the observed difference in events per count between the monotonic and cyclic

tests is improbably attributable to chance. However, the implication that more counts per event can be expected from concrete under monotonic load than under cyclic load should not be accepted without further investigation. The summary also indicates that the differences in the events per count recorded by the two transducers were of some but lesser significance. This may be attributable to the dependence of this parameter on the specific characteristics of individual transducers as well as the source mechanism generating the acoustic emission (Dilipkumar, Gudimetla, and Wood 1979). Only a limited amount of data was collected on the hollow cylinder series (Figures 18 and 19). Although not conclusive, the slope of event versus counts changes for a primarily tension source. The slopes are tabulated in Table 1 for comparison.

Conclusions and Recommendations

19. A preliminary data base has been obtained from which basic acoustic emissions from sources in concrete can be studied. As the literature indicates, a great many more tests are necessary to establish a set of empirical predictive equations. In the test in which tension was the predominant cause of the events that yielded the emissions, a marked change is shown in the slope of the counts versus events. Using this change as a preliminary indicator, progression of tensile cracking could be detected and monitored.

20. For field applications, additional work using acoustic transducers of different resonant frequencies is needed. Inexpensive ways of recording and storing data are also needed. The authors have experimented with the idea of heterodyning the 140-kHz signals to a more manageable audio frequency where they can be recorded at a much lower tape speed, resulting in a significant saving. The lower frequency data should be directly related to the 140-kHz data.

21. Tests of prototype concrete structures are needed to measure the amplitude and frequency of the background noise and rates of attenuation.

22. In summary, acoustic emission analysis has not yet been well

developed as a technique for the evaluation of phenomena taking place in concrete in structures. There exists a need for fundamental laboratory tests to identify the mechanism of transmission of the vibrations through concrete.

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Table 1

Events per Thousand Counts

Compressive Test	No. of Events Transducer 1	Transducer 2
Monotonic Loading		
4	32.0	56.9
5	51.4	80.3
7	32.4	53.7
6	50.0	76.9
Mean	41.5	67.0
Cyclic Loading		
10	71.4	73.7
11	75.0	76.9
9	72.5	64.2
8	69.2	72.0
Mean	72.0	71.7

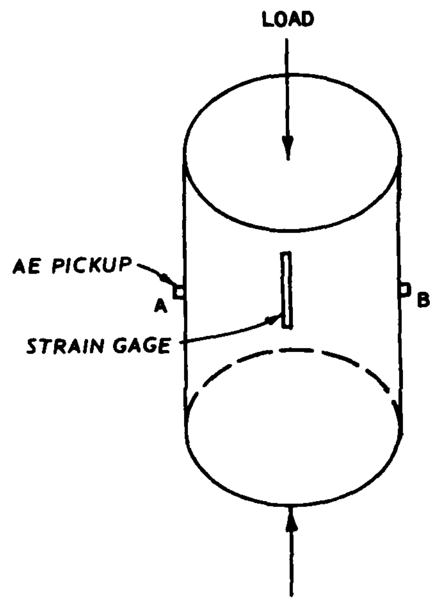
Note: The averaged number of events for both transducers was 35.3 for the biaxial monotonic load.

Table 2

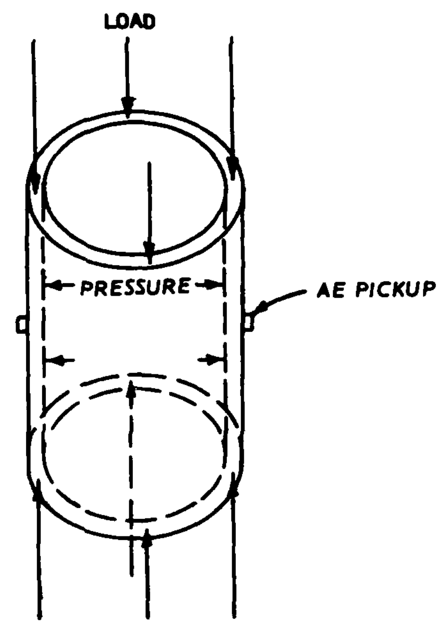
<u>Analysis of Variance of Acoustic Emission</u>

<u>Data From Compression Tests</u>

Source	Degrees of Freedom	Sum of Squares	Mean Square	Variance Ratio F	Significance Level
Total	15	3547	--	--	--
Monotonic-cyclic effect	1	1247	--	14.9	0.002
Transducer 1-2 effect	1	633	--	7.6	0.017
Interaction	1	666	--	8.0	0.015
Error	12	1001	83.4	--	--



a. TEST OF UNIAXIALLY LOADED CYLINDER



b. TEST OF BIAXIALLY LOADED CYLINDER

Figure 1. Test geometry

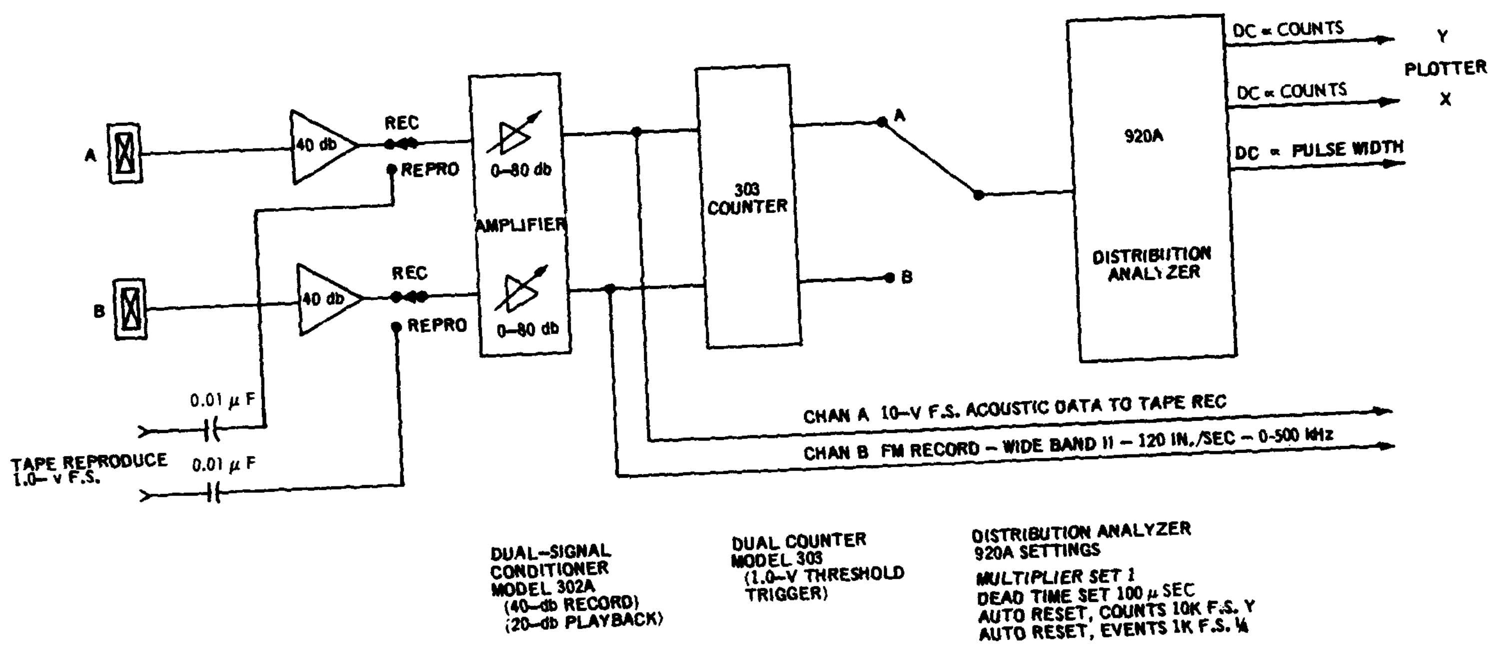


Figure 2. Diagram of acoustic emission measurement system

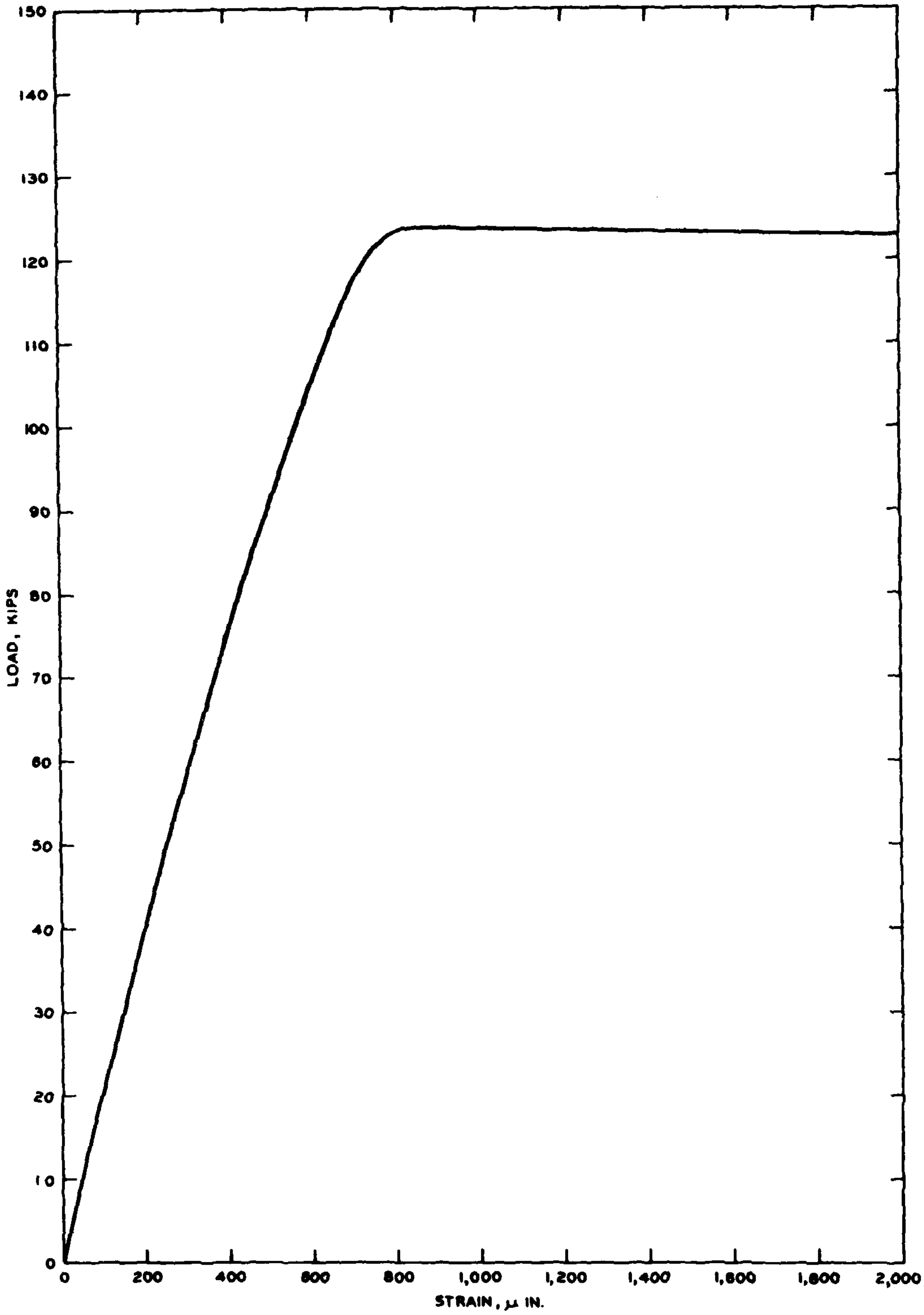


Figure 3. Strain versus load, 60 kips/min, cylinder BS-2, Test 1

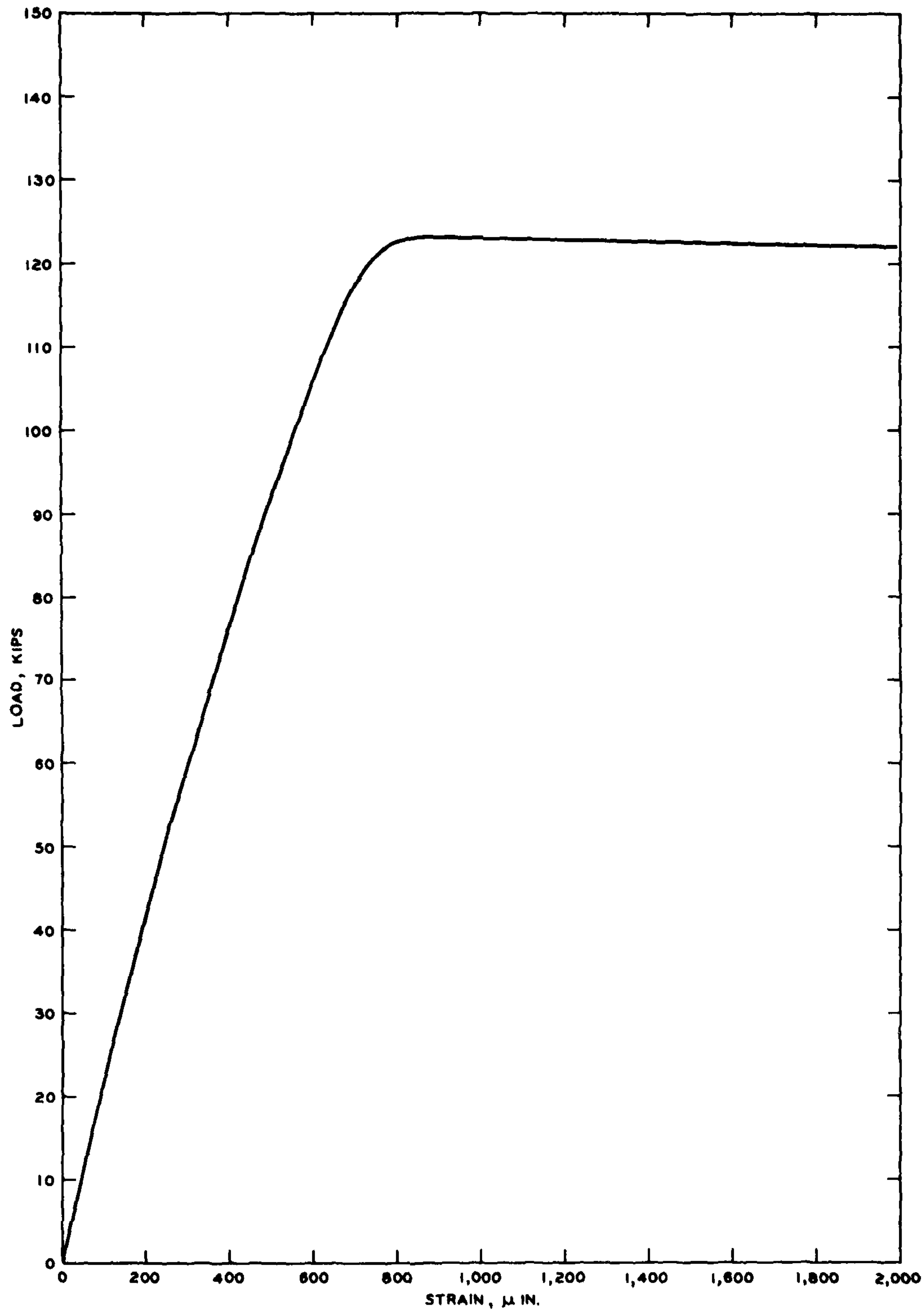


Figure 4. Strain versus load, 60 kips/min, cylinder BS-14, Test 2

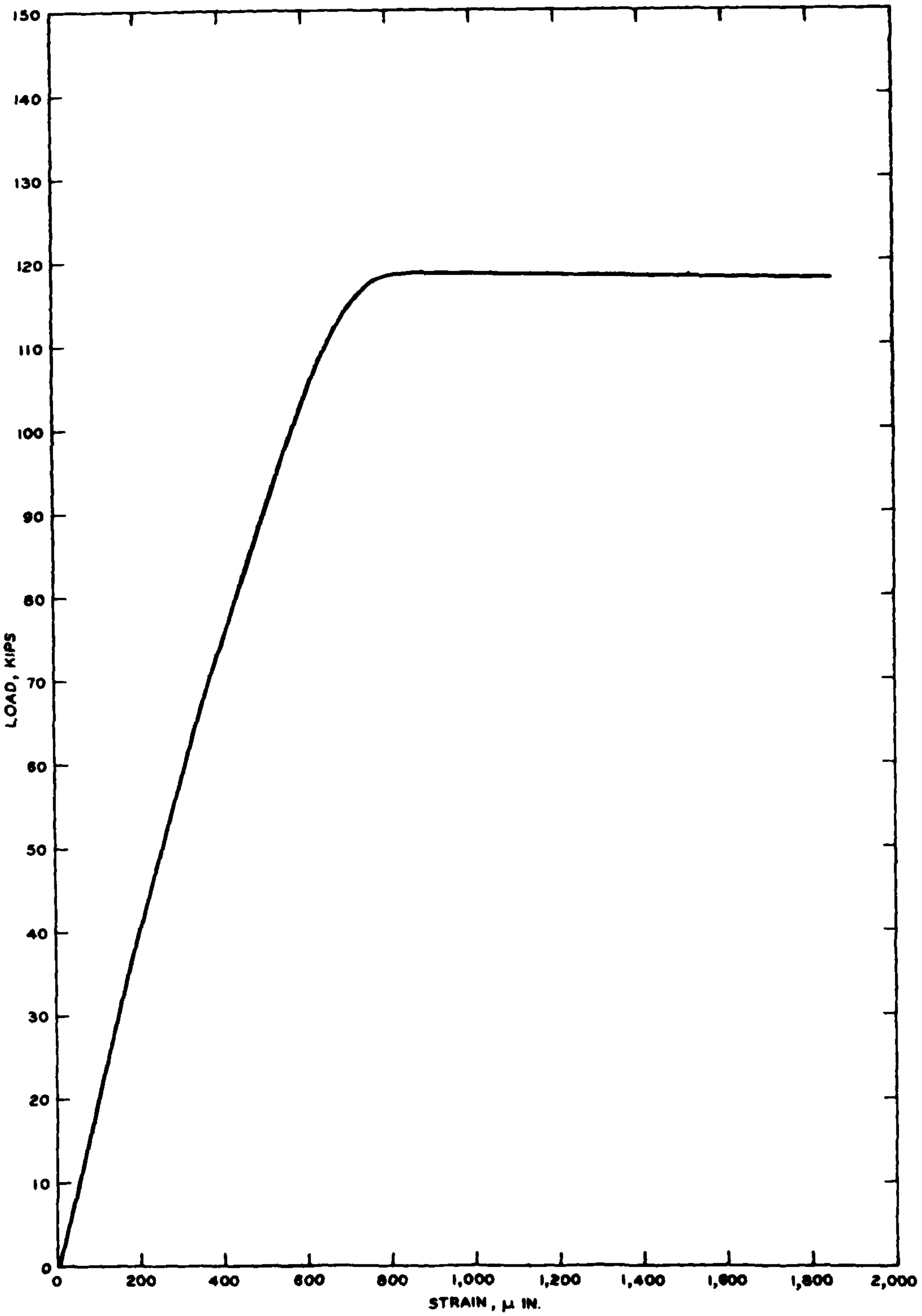


Figure 5. Strain versus load, 60 kips/min, cylinder BS-10, Test 3

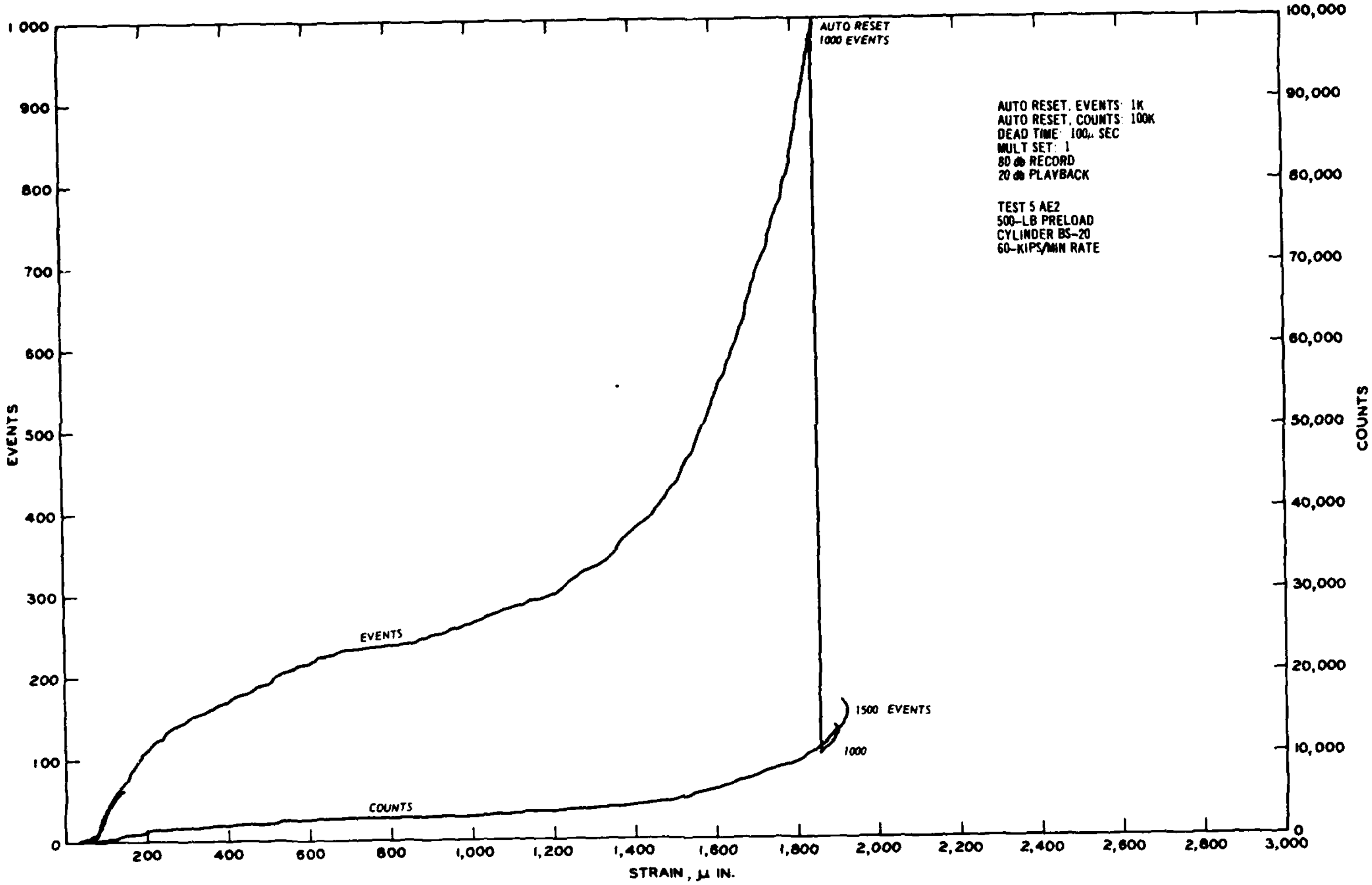


Figure 6. Monotonic loading data, first transducer

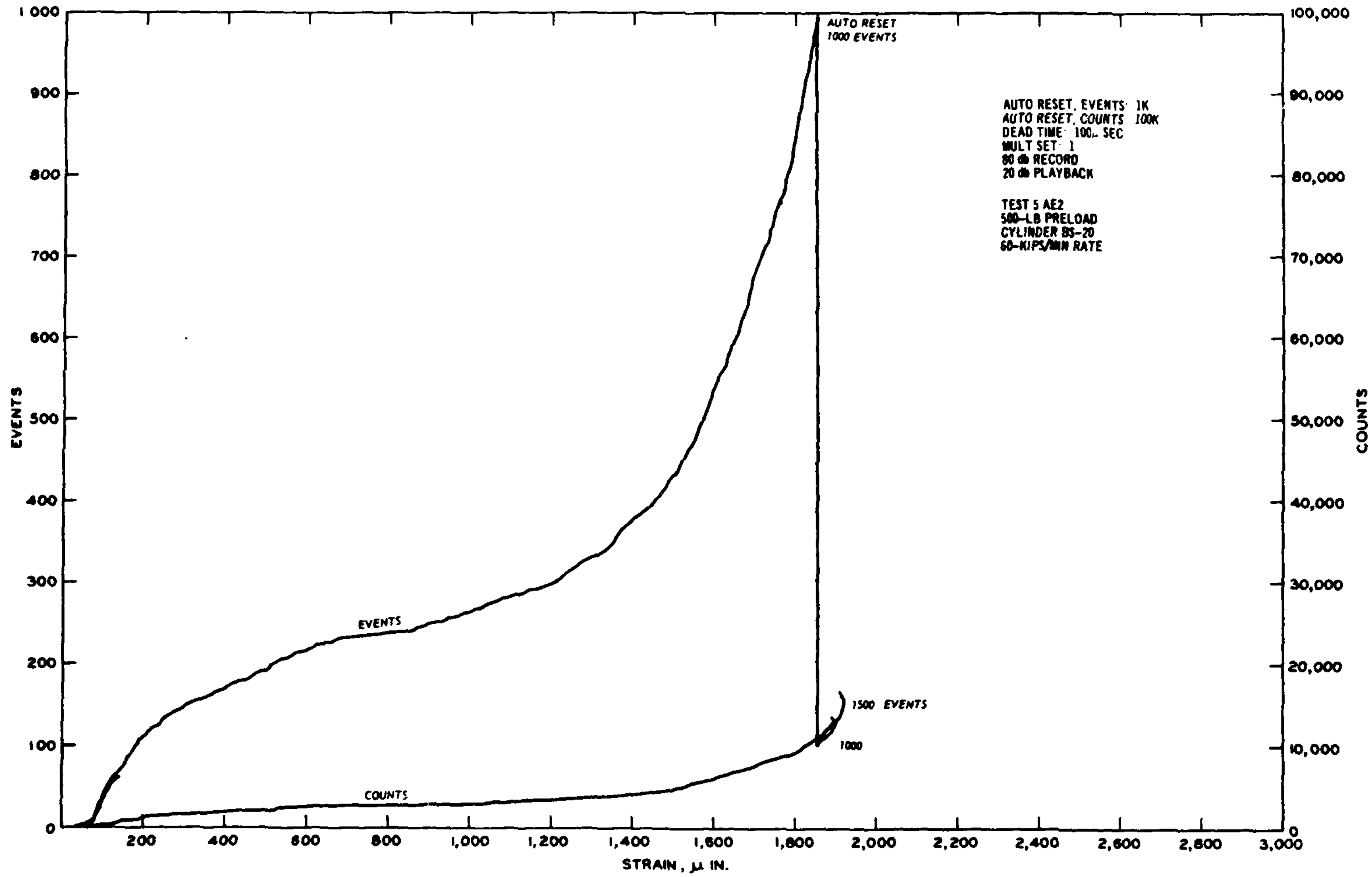


Figure 7. Monotonic loading data, second transducer

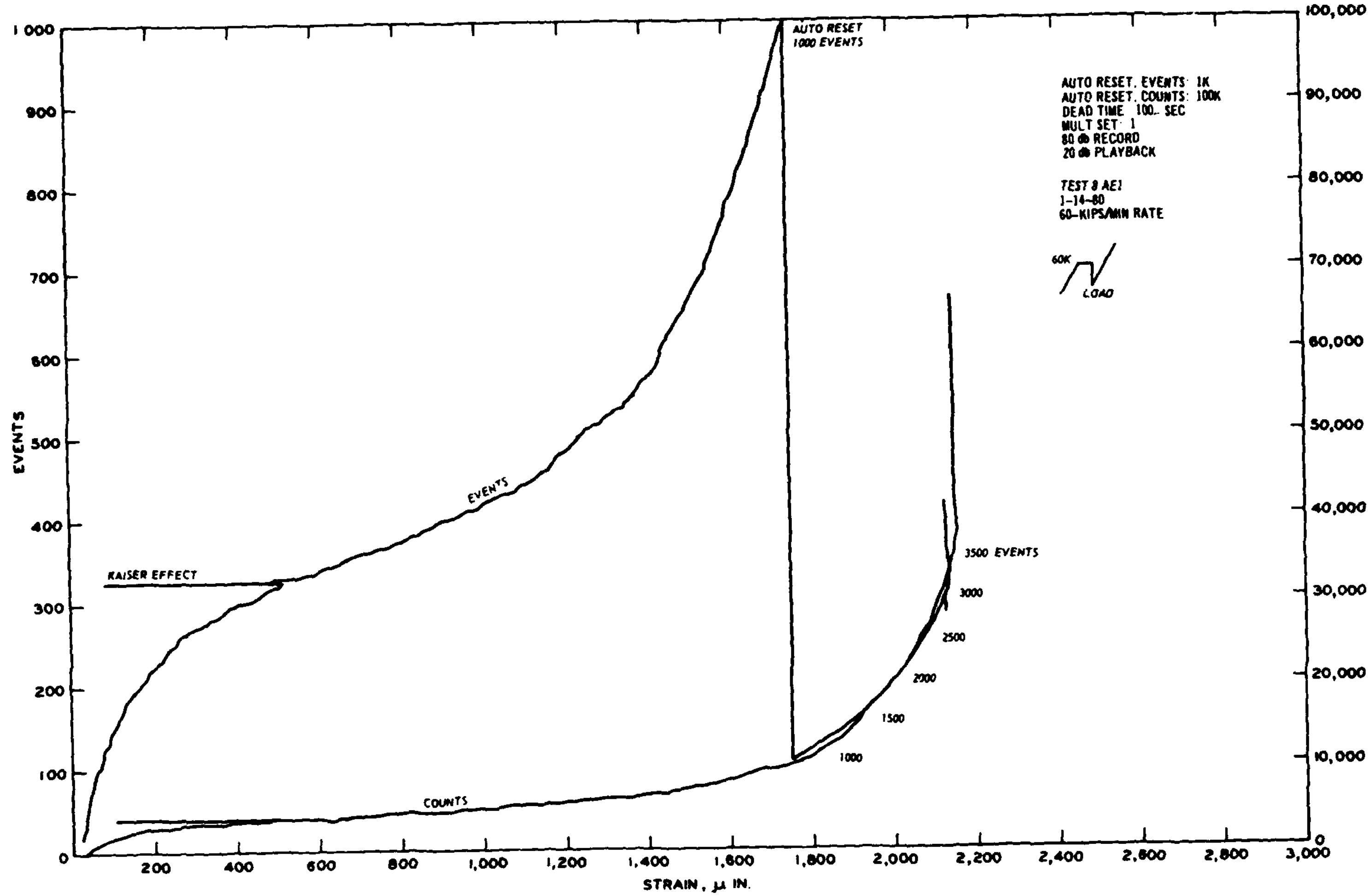


Figure 8. Cyclic load data, Test 8, first transducer

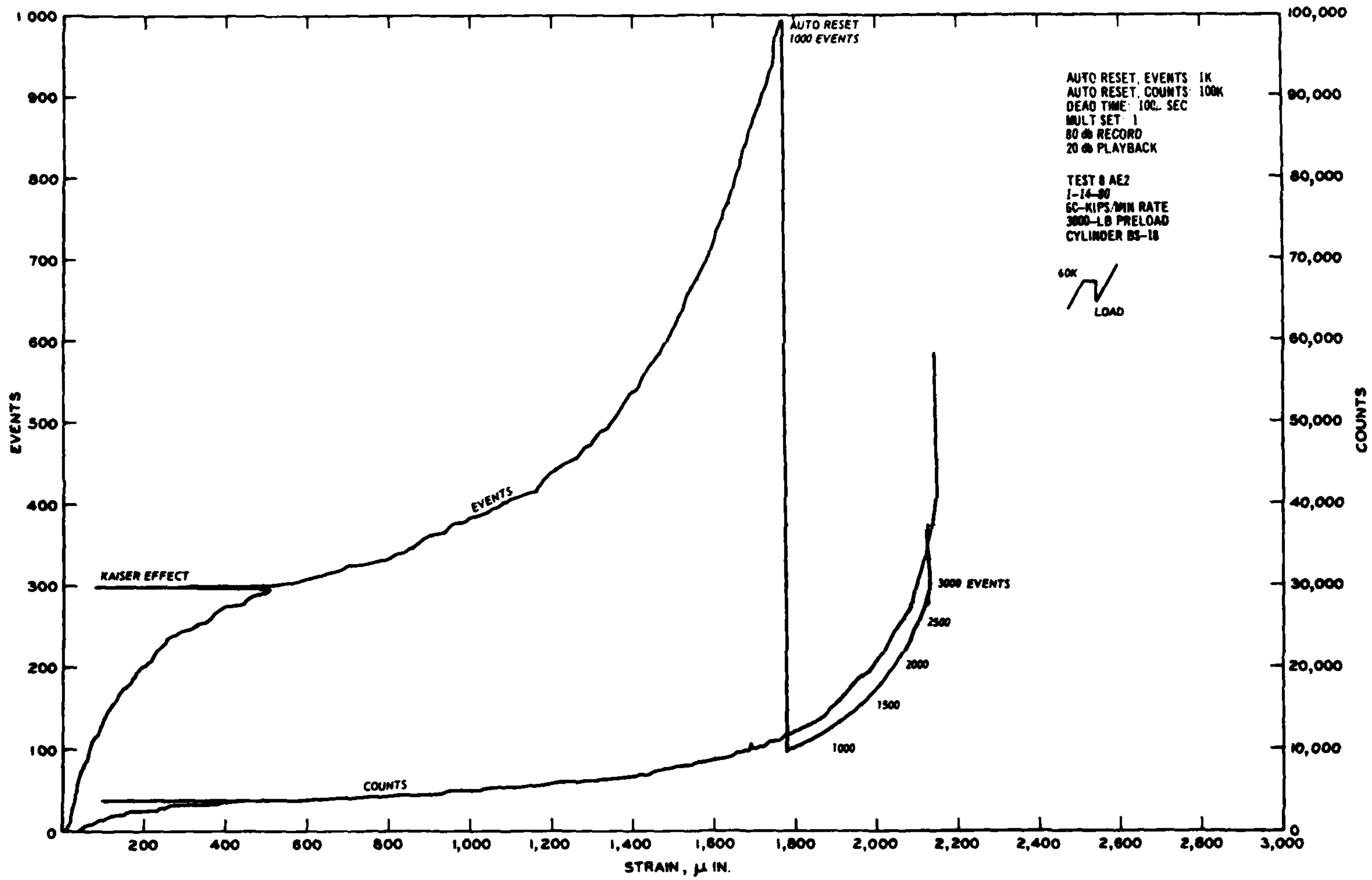


Figure 9. Cyclic load data, Test 8, second transducer

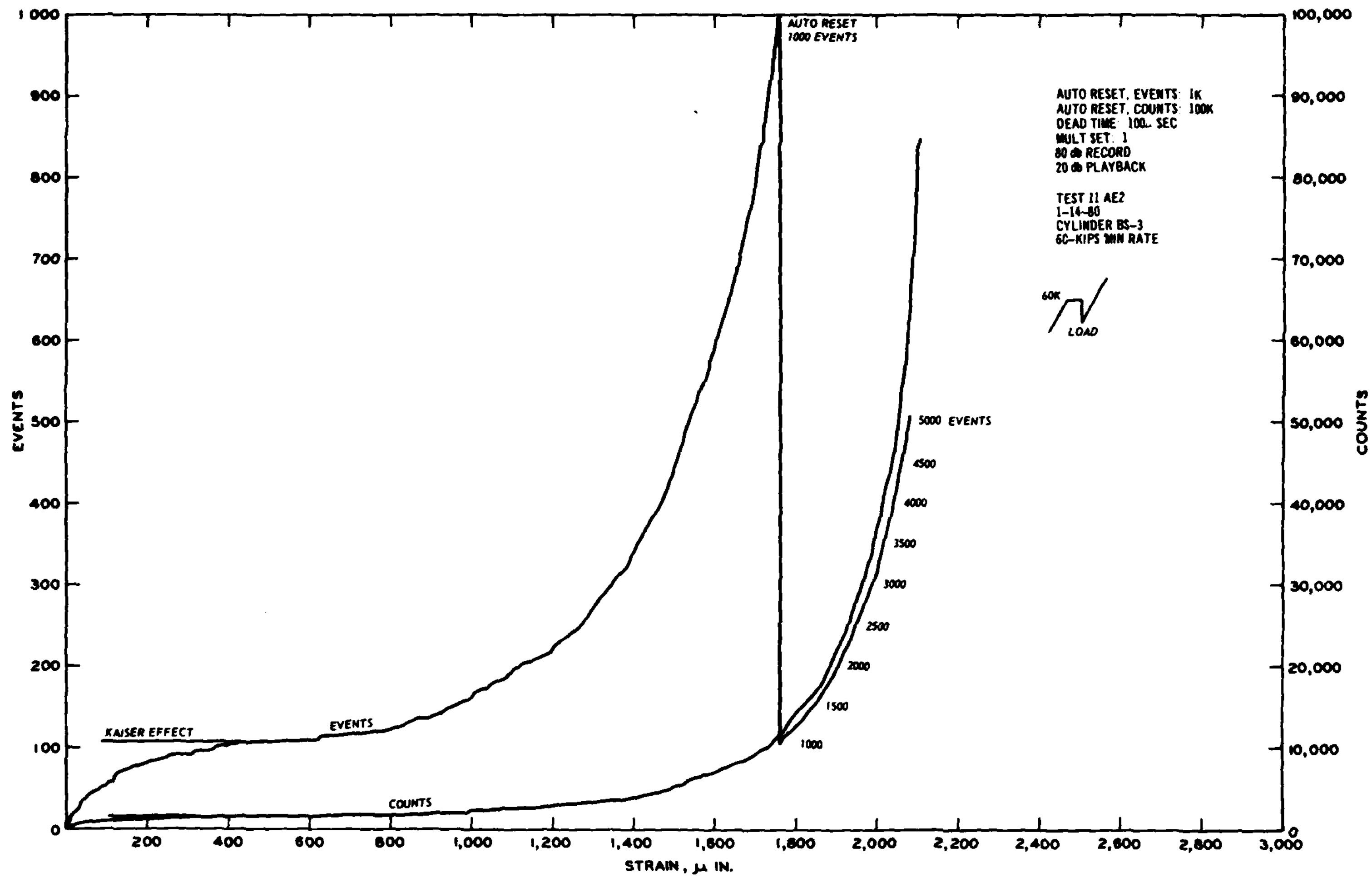


Figure 10. Cyclic load data, Test 11, second transducer

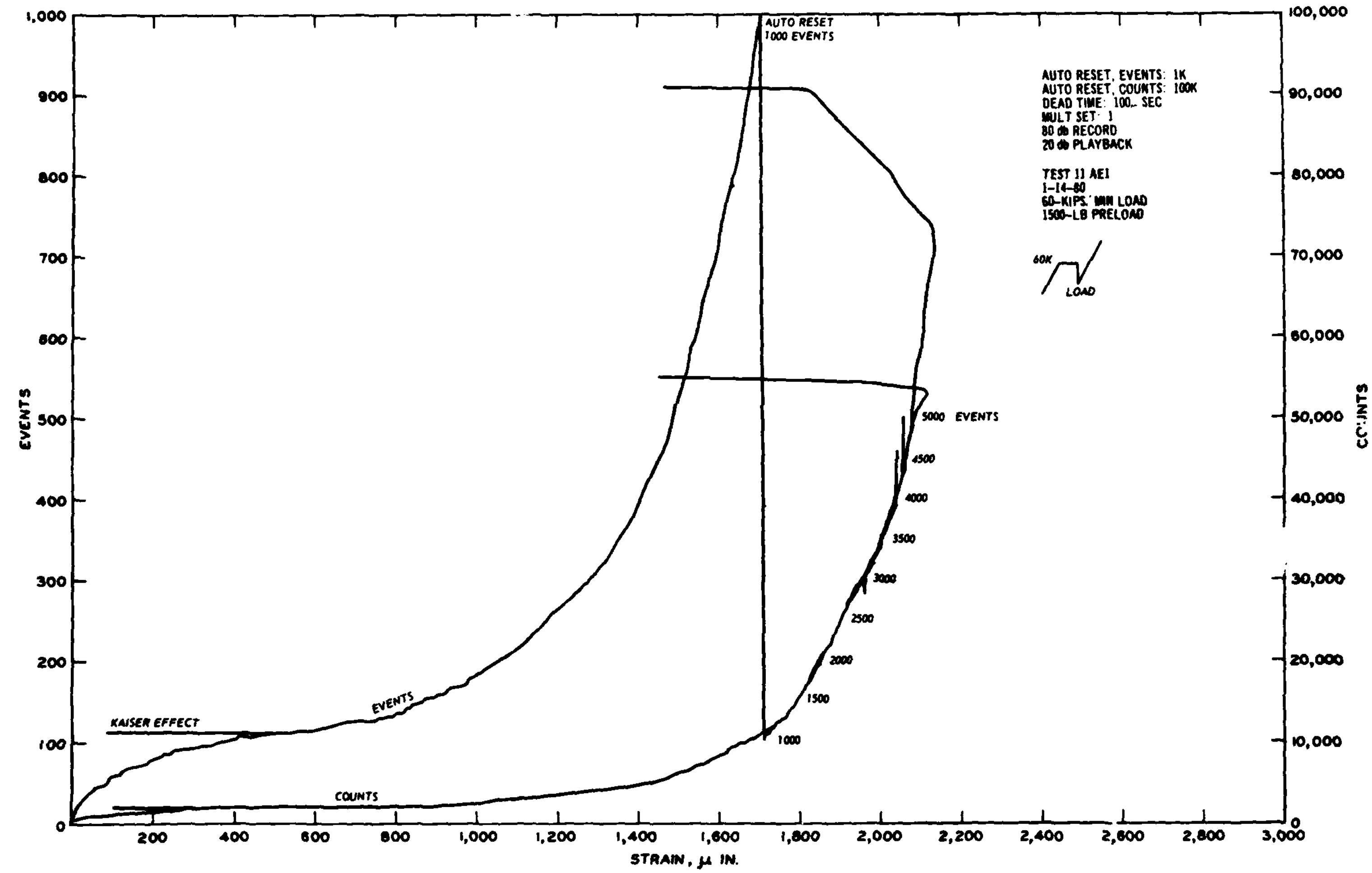


Figure 11. Cyclic load data, Test 11, first transducer

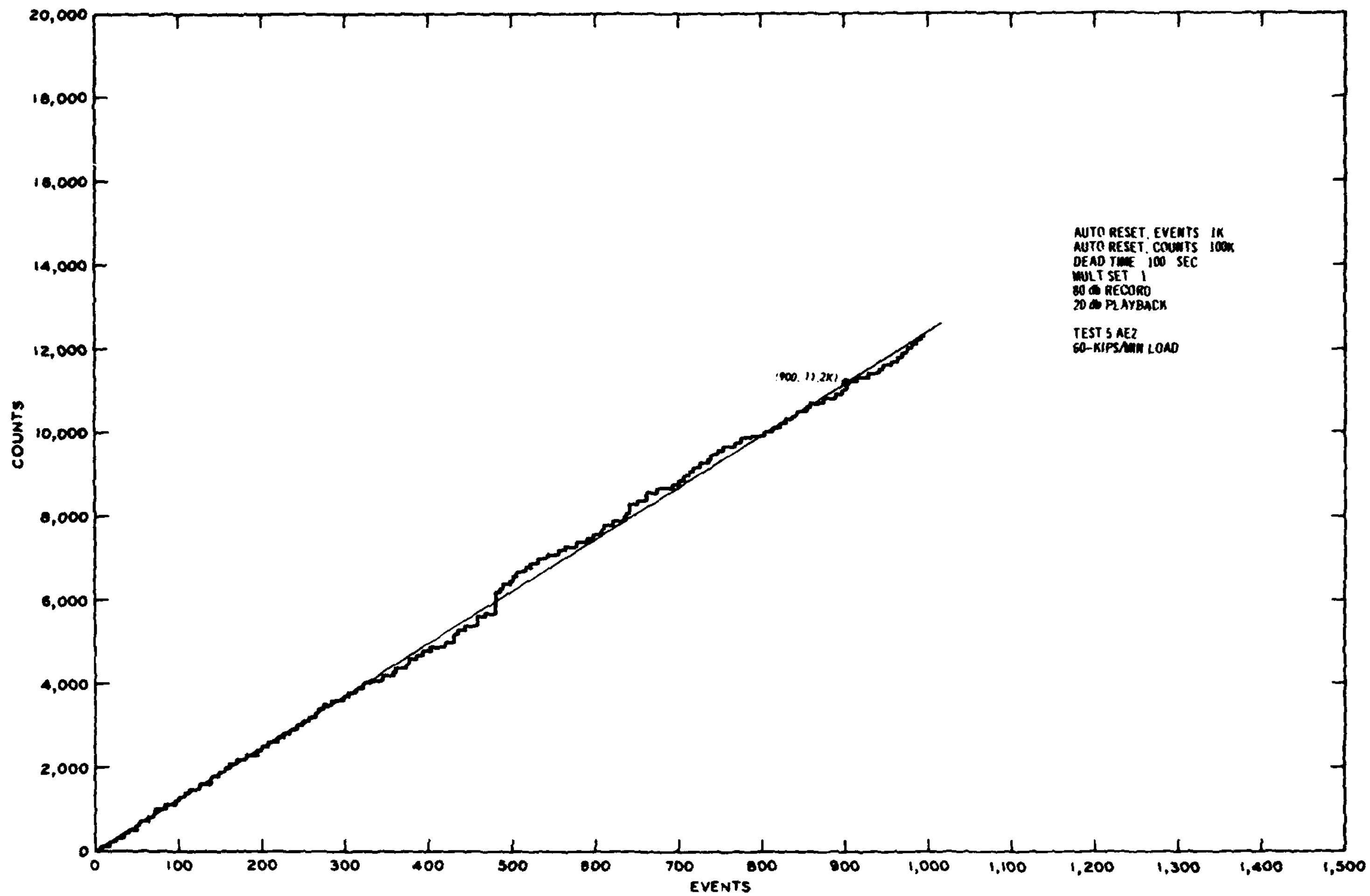


Figure 12. Cumulative counts versus cumulative events, Test 5, second transducer

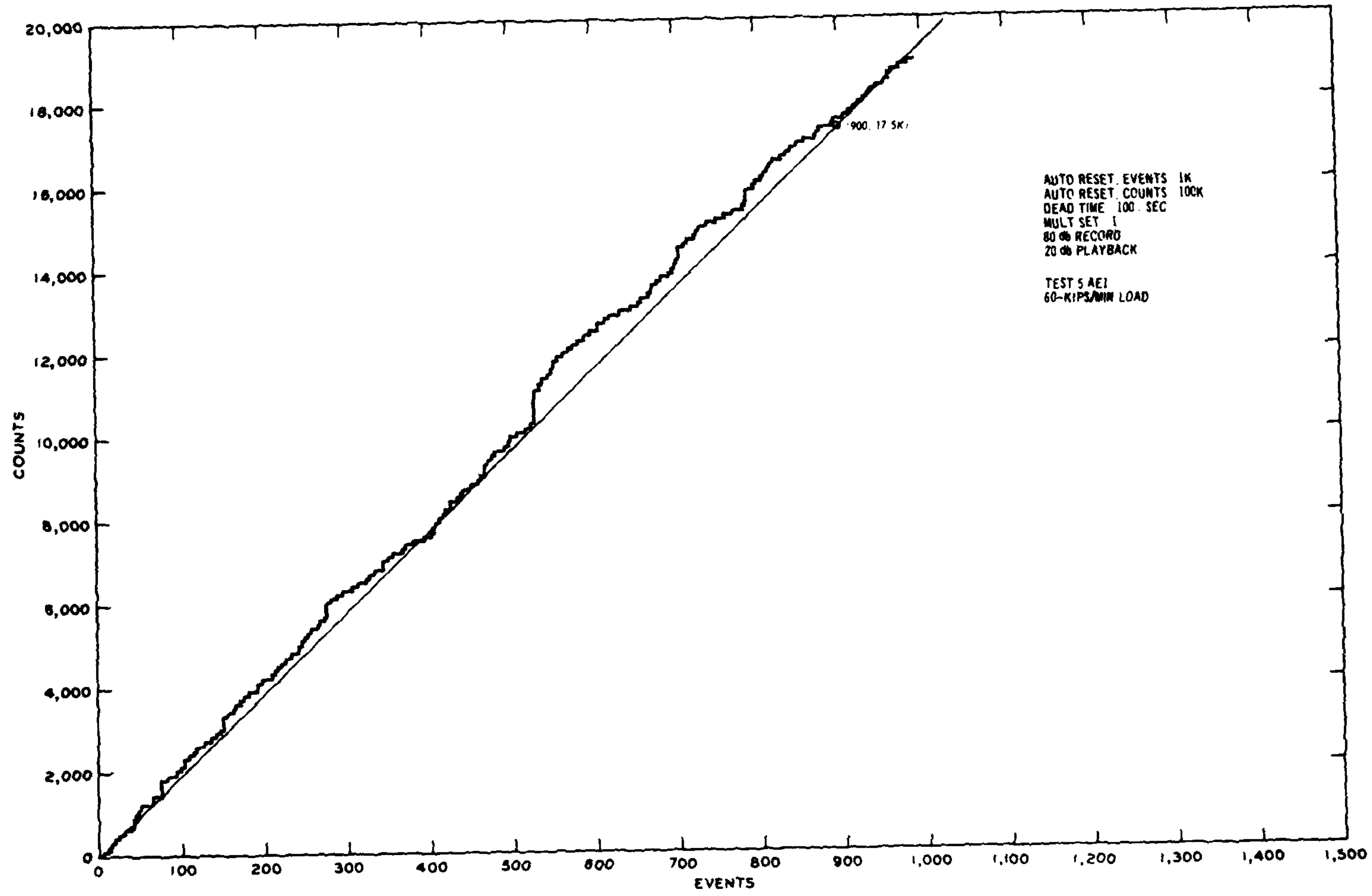


Figure 13. Cumulative counts versus cumulative events, Test 5, first transducer

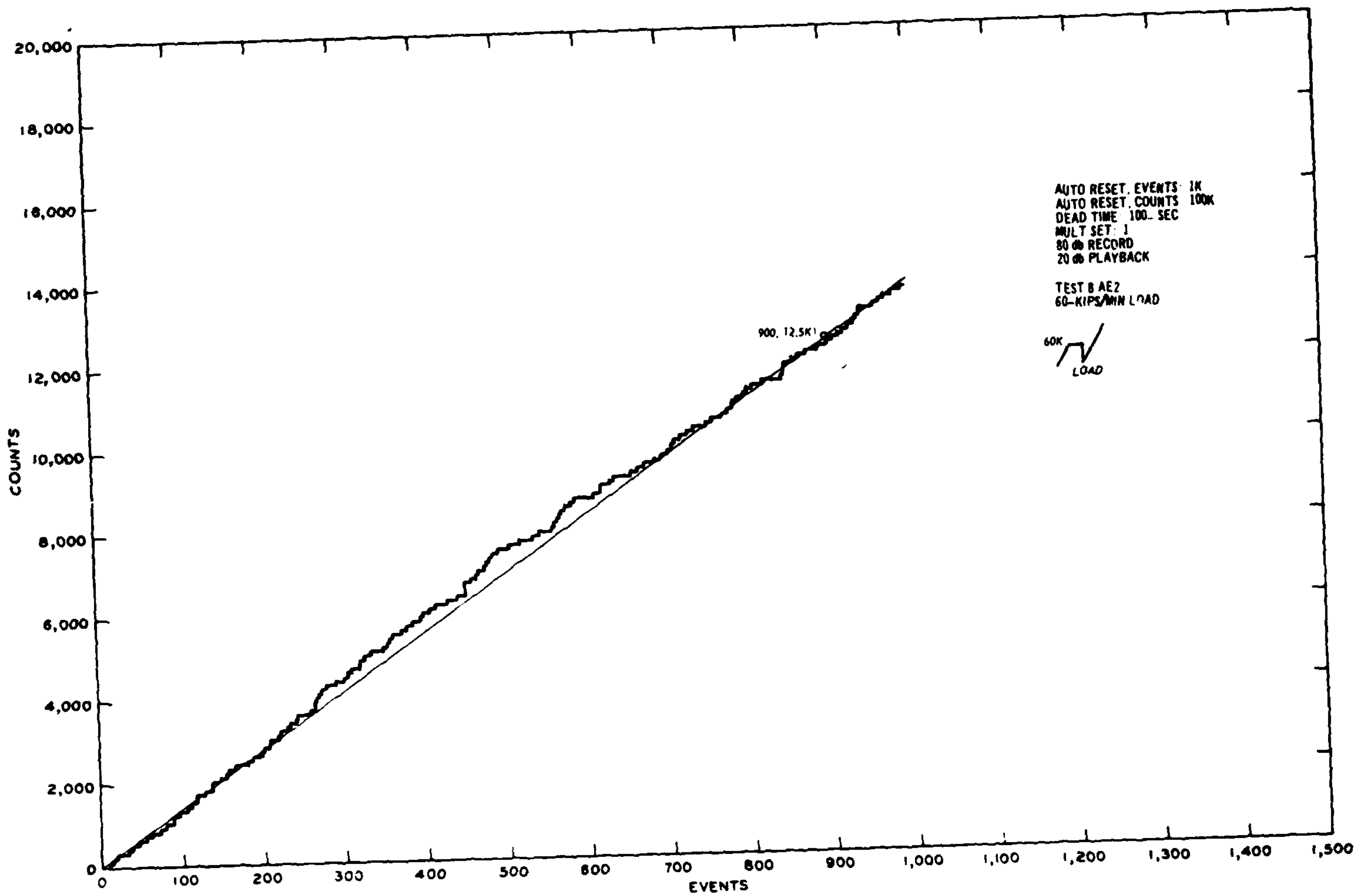


Figure 14. Cumulative counts versus cumulative events, Test 8, second transducer

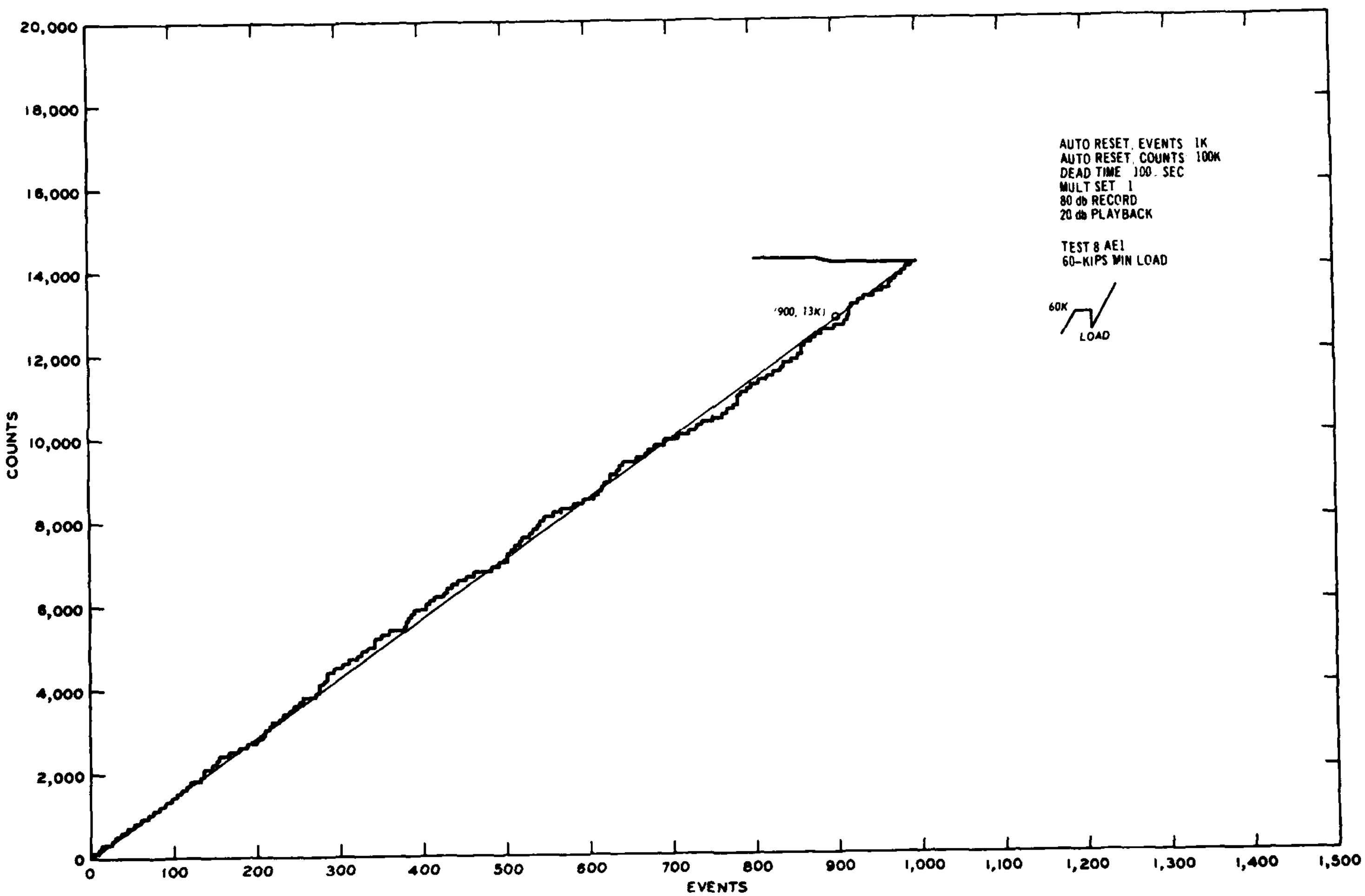


Figure 15. Cumulative counts versus cumulative events, Test 8, first transducer

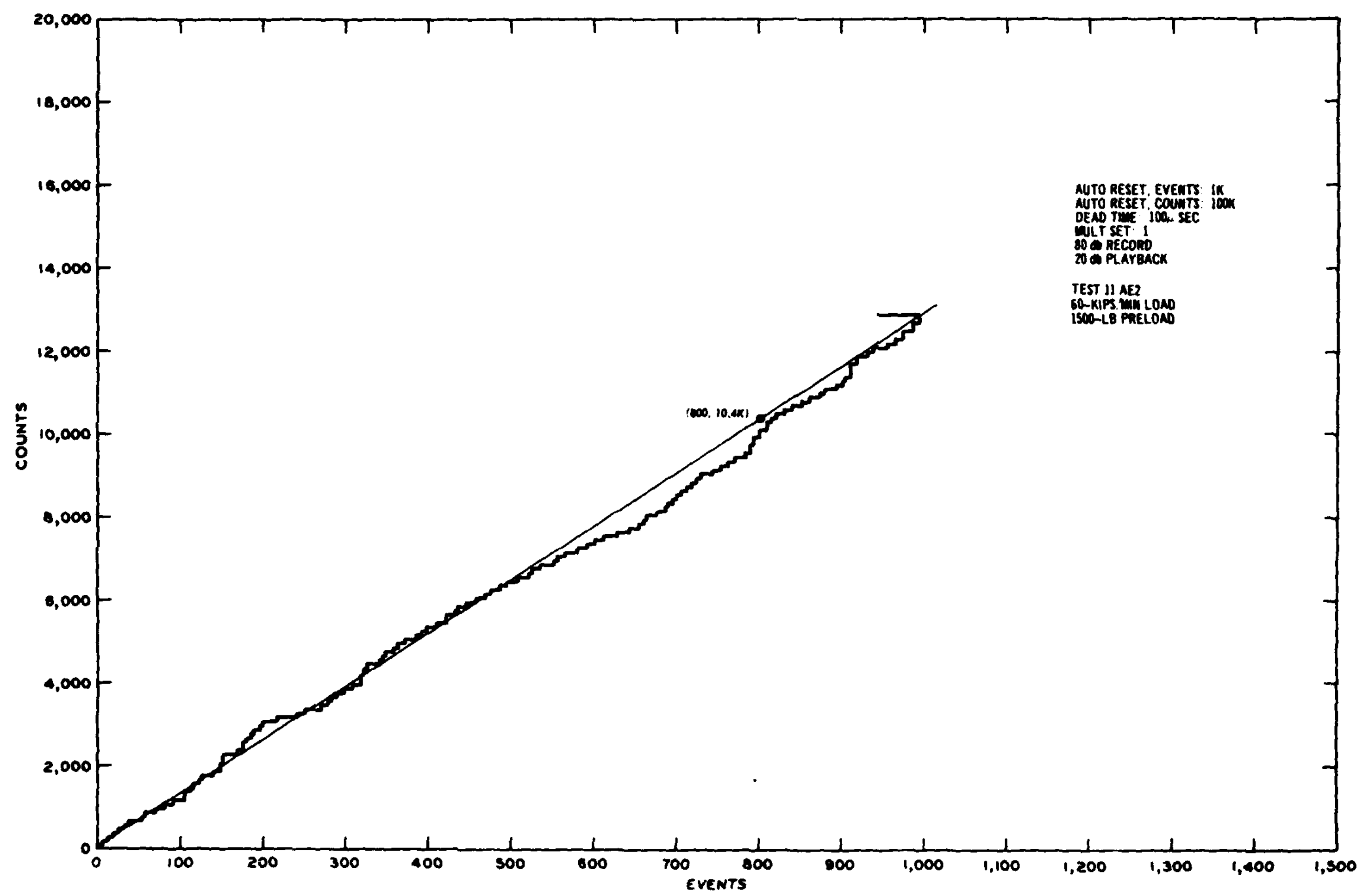


Figure 16. Cumulative counts versus cumulative events, Test 11, second transducer

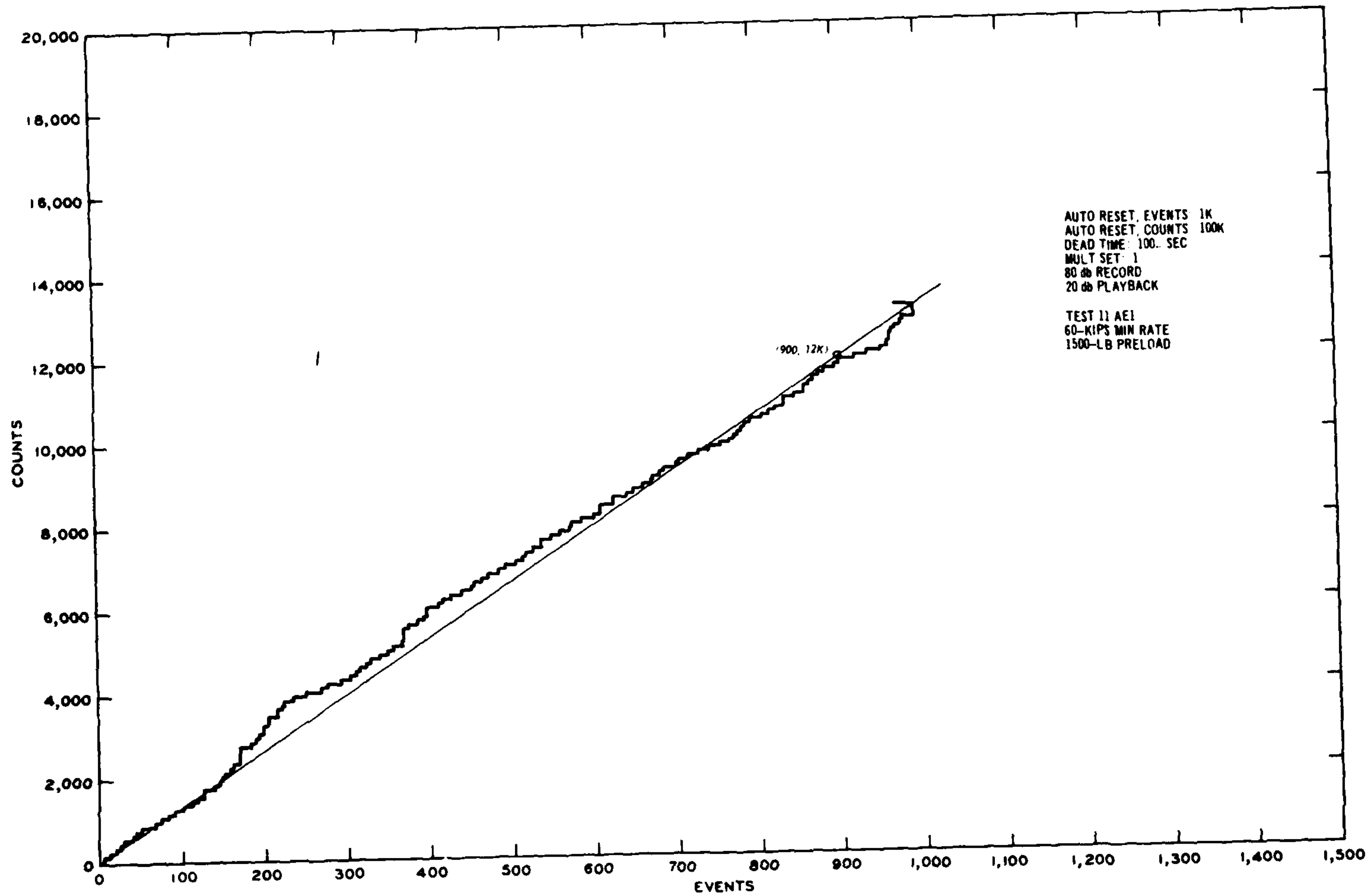


Figure 17. Cumulative counts versus cumulative events, Test 11, first transducer

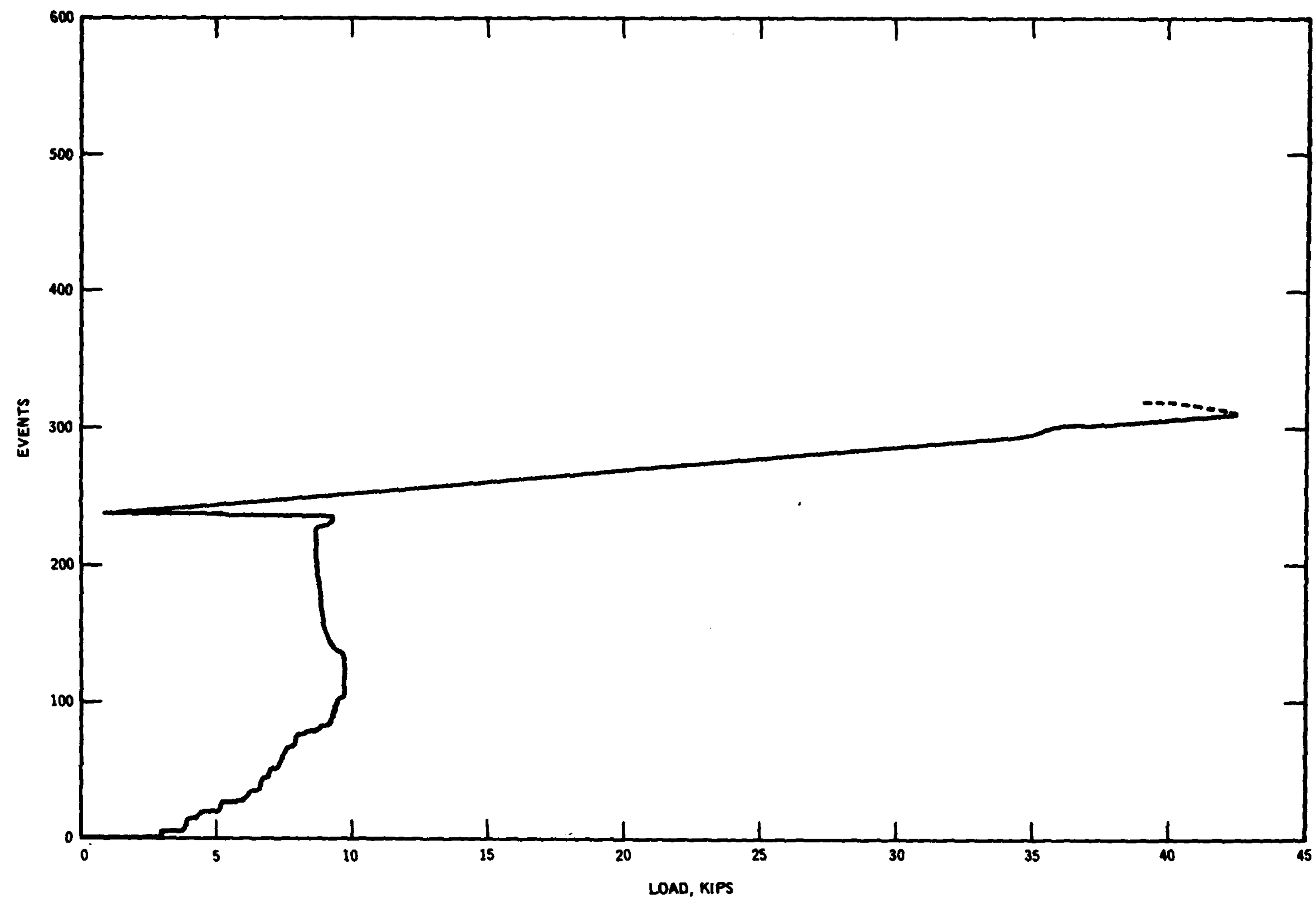


Figure 18. Events versus load, Test T2, first transducer

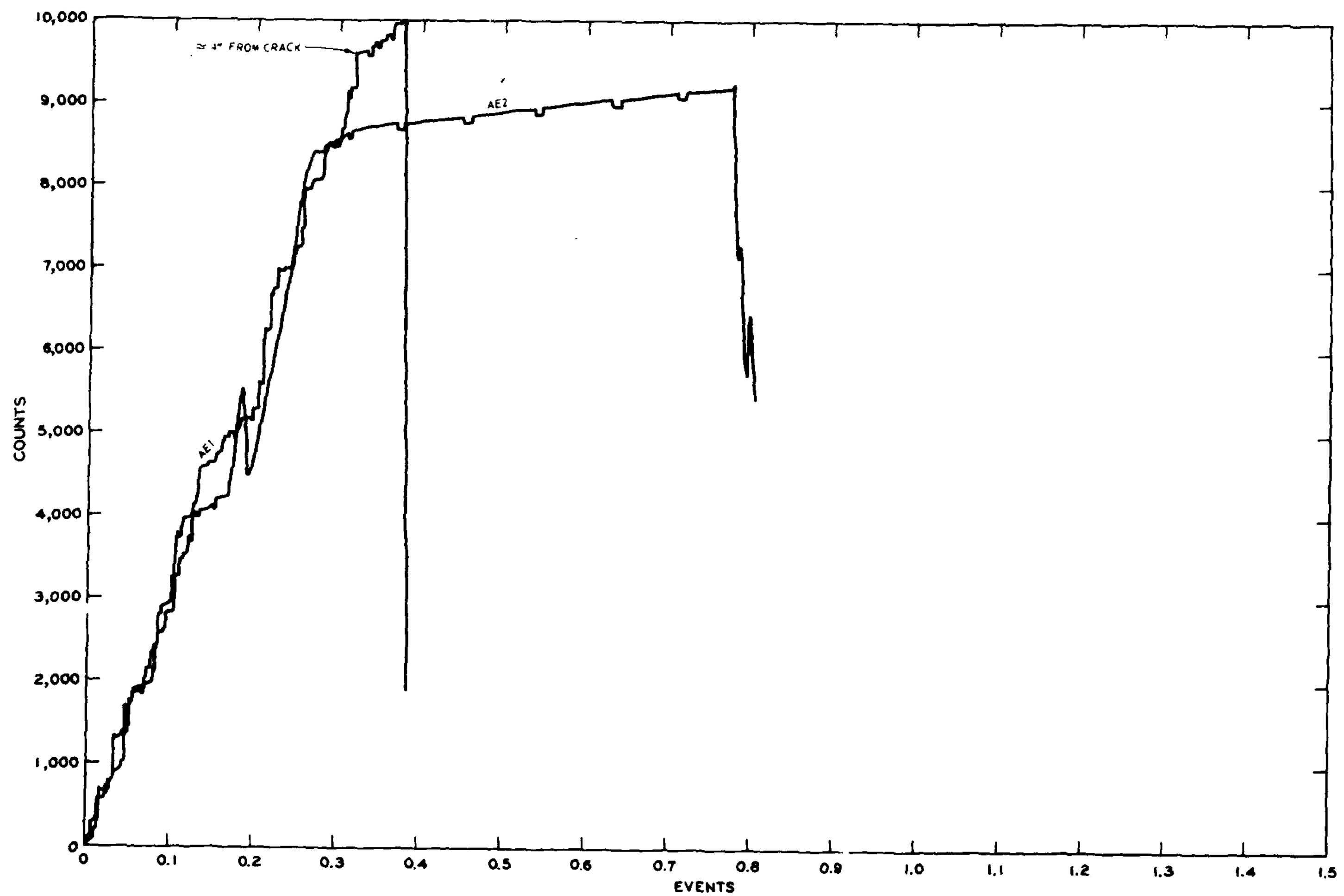


Figure 19. Events versus counts, Test T2, 26 db

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Mlakar, P.F.
  Acoustic emission from concrete specimens : final report / by P.F. Mlakar, R.E. Walker, B.R. Sullivan (Structures Laboratory, U.S. Army Engineer Waterways Experiment Station). -- Vicksburg, Miss. : The Station ; Springfield, Va. : available from NTIS, [1981].
  13, [21] p. : ill. ; 27 cm. -- (Miscellaneous paper / U.S. Army Engineer Waterways Experiment Station ; SL-81-26)
  Cover title.
  "September 1981."
  "Prepared for Assistant Secretary of the Army (R&D), Department of the Army, under Project 1A161101A91D."
  Bibliography: p. 12-13.

1. Acoustic emission testing. 2. Concrete--Testing. 3. Concrete construction. 4. Materials--Dynamic testing. I. Walker, R.E. II. Sullivan, B.R. III. United States.

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  Acoustic emission from concrete specimens : ... 1981.

Office of the Army (Research and Development). IV. U.S. Army Engineer Waterways Experiment Station. Structures Laboratory. V. Title VI. *Series:* Miscellaneous paper (U.S. Army Engineer Waterways Experiment Station) ; SL-81-26.
TA7.W34m no.SL-81-26

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